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16. Abstract The factors which affect the designing of wind-driven power plants are discussed, including purpose and nominal output, wind velocity as a function of height, wind forces as a function of height, and the torques to be expected. Design features of the "ZYKLON" wind-driven power plants are summarized, and sample calculations are made, based on the "ZYKLON-D 30" project. The optimal shaft height for a 30-m wind turbine is found to be 50 m above ground, with a yearly output of 2,125,000 kWh at a cost of 2.68 German pfennigs per kWh.

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PRINCIPLES OF STEEL CONSTRUCTION ENGINEERING IN THE BUILDING AND OPERATION OF WIND-DRIVEN POWER PLANTS

Helmut Voigt

Translation of "Die stahlbautechnischen Grundlagen im Bau und Betrieb von Windkraftwerken," Der Stahlbau, Vol. 23, No. 8, August 1954, pp. 184-188

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
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II

PRINCIPLES OF STEEL CONSTRUCTION ENGINEERING IN THE BUILDING AND OPERATION OF WIND-DRIVEN POWER PLANTS

Helmut Voigt

The building and operation of wind-driven power plants (WPPs)/184* must be considered a current subject, because general interest is being devoted to a greater extent to the exploitation of wind power, due to the incessantly rising prices of coal and oil, and the large-scale use of WPPs can be expected to begin in favorably located areas, since the associated technical problems can be considered solved at the present state of the art.

1. The General Size of Wind-Driven Power Plants

The former "German Study Group on Wind Power," Berlin, classified WPPs as very small WPPs with an installed power of up to 1 kW, small WPPs producing 1 to 100 kW, medium WPPs producing 100 to 1000 kW, and large WPPs producing more than 1000 kW. The advocates of small WPPs are of the opinion that WPPs can only achieve economic importance in those places where a power network does not exist or where connecting individual consumers to a power system produces excessive costs. Small WPPs have occasionally been built and put into operation. Their installed power is generally much less than 100 kW. They are almost all dc WPPs which permit storage of the current in batteries. The capacity of the storage batteries is limited, due to their relatively high costs. Thus dc WPPs with storage batteries are also only economical in the form of small WPPs. An exception is the Russian "TWO-D 30" WPP in Balaklava, on the Crimean Peninsula, which is operated as a three-phase WPP in conjunction with a small water power station and reaches 92 kW with a wind turbine (WT) diameter of 30 m.

Another viewpoint which is held is that only large WPPs can be a factor in the energy industry. Examples to be mentioned are

*Numbers in the margin indicate pagination in the foreign text.

the large WPP projects of Honnef and Kleinhenz. The installed power of the large "Kleinhenz-MAN" WPP [1] is 18,000 kW for a wind turbine diameter of 130 m and an operating height of 200 m. Large WPPs are meant to operate in conjunction with steam and hydroelectric plants, via a grid system, and are therefore designed as three-phase WPPs. The grid system receives the wind-generated current in each case, eliminating the problem of power storage.

If we consider the large-scale use of WPPs, particularly for public power supply, the general size of WPPs is determined by the economic optimum with which a kilowatt-hour is produced. Kleinhenz's article [1] provides a survey of the problems associated with WTs with very large dimensions which result from the interaction of air forces, inherent loads, and inertial, centrifugal and gyroscopic forces. A greater risk lies in the danger of vibration which exists for these dimensions, however, theoretical consideration of which does not offer adequate safety, due to the simplifying assumptions which are made. WT diameter must also be restricted for other reasons. Since the peripheral speed u of the WT is not supposed to exceed a certain multiple of wind velocity v, exceeding a speed ratio of $u/v = 6$, the rotational speed n of the WT decreases linearly with its radius R. The torques and thus the forces to be transmitted from the WT to the generators via the gearbox increase inversely in accordance with the power equation $N = M_d \cdot \omega$. In the Kleinhenz project, peak torque is $M_{d\,max} = 1670$ tm at $N_{max} = 18{,}000$ kW and $n = 10.5$ rpm.

The high torques of WTs are also the reason why the generators are housed in a nacelle directly behind the WT, and not at the base of the WPP, for example. The torque is taken off with the greatest possible radius at the nacelle periphery, normally amounting to 10% of the WT's radius. All of these problems which increase with increasing WT diameter are also accompanied by storage, transport and installation problems. At the present state of the art, WTs

with diameters of up to 30 m can be easily produced and reliably operated taking the above factors into consideration. The Russian "TWO-D 30" WPP, with a 30-m WT, has been in operation since 1931. In contrast to the WT, the supporting structure, generally a guyed tubular mast, does not present special problems in steel construction engineering, even for operating heights of 200 m. The operating height of a WT is therefore primarily a question of economy.

2. The Economically Optimal Operating Heights of Wind Turbines /185

An optimal WT operating height can be predicted for each WT diameter using the given meteorological conditions. Wind velocity v increases with height above the ground. For regions with strong winds, the distribution of wind with height as shown in Fig. 1 can be taken as a basis. The shape of this curve is represented with sufficient accuracy by the formula $v = 2.7 \cdot \sqrt[5]{H} = 2.7 \cdot H^{0.2}$. At any height H_X, we obtain the following equations with respect to an assumed reference height H_0:

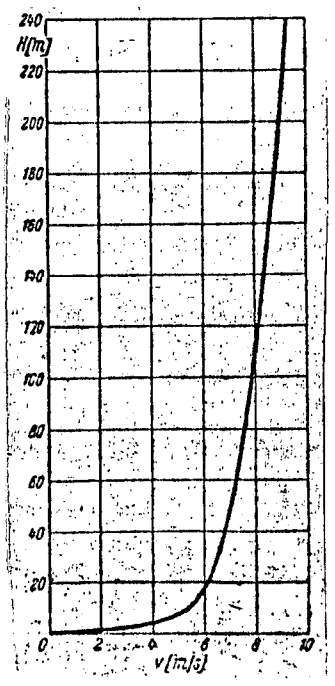

Fig. 1. Increase in wind with height above the ground.

Wind velocity since $v \propto H^{0.2}$, $v_x = v_0 \cdot \left(\frac{H_x}{H_0}\right)^{0.2}$,

Dynamic pressure since $q \propto v^2 \propto H^{0.4}$, $q_x = q_0 \cdot \left(\frac{H_x}{H_0}\right)^{0.4}$,

Power since $N \propto v^3 \propto H^{0.6}$, $N_x = N_0 \cdot \left(\frac{H_x}{H_0}\right)^{0.6}$,

Since the achievable power N_X increases as v^3 or $H^{0.6}$, energy yield increases continuously with the operating height of the WT. However, manufacturing, shipping and installation costs, and thus yearly overhead, also increase with operating height. If costs were to increase in the same manner as the power which is obtained,

i.e., as $(H_x/H_0)^{0.6}$, structural height would be immaterial. Since there are items in the schedule of costs which increase at a rate which is less than, equal to or greater than $(H_x/H_0)^{0.6}$, however, an optimal operating height exists at which the lowest costs for power generation can be achieved. Those items which increase at a greater rate than as $(H_x/H_0)^{0.6}$ reduce optimal operating height; those which increase at a lesser rate raise the WT, while those items which increase as $(H_x/H_0)^{0.6}$ have no effect on the most favorable operating height for the WT. The optimum vertical position of a 30-m WT has been calculated on the basis of the "ZYKLON-D 30" WPP project. A brief description will be given at the end of this article. The reference height is taken as H_0 = 50 m on /186
the basis of practical and mathematical considerations. Since H_0 = 50 m is likely to lie close to the optimum, a schedule of materials, weights and costs for the "ZYKLON-D 30" WPP is first determined with a WT height of 50 m, on which the subsequent calculations are based (Table 1).

Values for structural heights of H = 30, 40, 60 and 70 m are obtained from the data in columns 9 and 10 on the basis of the price-increase factors in column 4, using the conversion factors $(H_x/H_0)^k$ in Table 2. The price-increase factors selected represent probable values obtained from practice. Slight deviations in the choice of price-increase factors from actual practical conditions will largely cancel one another out. An appreciable effect on the final results is not to be expected from this. The important thing is that the items which are decisive in determining the total production costs, such as blade spars, hub spiders, gearboxes, generators, tubular masts, guy cables and foundations, are applied in a manner appropriate for the construction heights. The price-increase factor $(v3)^{3/4}$ = $= (H_x/H_0)^{0.45}$ was used for the largest item, the generators (item 7), for example. This value is generally used for electrical machinery and means that the price of an electrical machine increases as its power raised to the 3/4 power, i.e. as $N^{3/4} \propto (v3)^{3/4}$, since power increases as v^3 in WPPs.

TABLE 1

1		3	4	5	6	7	8	9	10	11	12	13	14
	Height of Wind Turbine			$H_x = 30$ m; $\frac{H_x}{H_o} = 0{,}6$		$H_x = 40$ m $\frac{H_x}{H_o} = 0{,}8$		$H_o = 50$ m $\frac{H_x}{H_o} = 1{,}0$		$H_x = 60$ m $\frac{H_x}{H_o} = 1{,}2$		$H_x = 70$ m $\frac{H_x}{H_o} = 1{,}4$	
Item	Components and Overhead	Price factor	$\left(\frac{H_x}{H_o}\right)^k$	Wt. (t)	Price (DM)	Wt. (t)	Price (DM)	Wt. (t)	Price (DM)	Wt. (t)	Price (DM)	Wt. (t)	Price (DM)
1	1 Generator nacelle	c^2	$k = 0{,}4$	2,45	1 835	2,74	2 057	3,00	2 250	3,23	2 420	3,43	2 575
2	3 Blade spars	c^2	0,4	8,60	25 700	9,60	28 800	10,50	31 500	11,30	33 900	12,00	36 000
3	3 Sets blade covering	c^2	0,4	2,45	7 340	2,74	8 230	3,00	9 000	3,23	9 680	3,43	10 300
4	1 Hub spider	c^2	0,4	4,90	14 680	5,49	16 460	6,00	18 000	6,45	19 350	6,87	20 600
5	1 Turbine shaft with bearings	c^2	0,4	2,04	6 120	2,23	6 860	2,50	7 500	2,69	8 070	2,86	8 580
6	1 Gearbox	c^3	0,6	3,68	11 010	4,33	13 120	5,00	15 000	5,58	16 700	6,12	18 350
7	3 Generators	$(c^2)^{3/4}$	0,45	9,53	37 070	10,84	43 400	12,00	48 000	13,00	52 000	14,00	55 800
8	1 Control wind turbine	c^2	0,4	0,82	4 080	0,91	4 570	1,00	5 000	1,08	5 380	1,14	5 720
9	1 Nacelle shaft	c^2	0,4	8,16	6 120	9,15	6 860	10,00	7 500	10,75	8 070	11,44	8 580
10	2 Wind roses with booms	c^2	0,4	2,45	7 340	2,74	8 230	3,00	9 000	3,23	9 680	3,43	10 300
11	1 Master bearing; 1 neck bearing	c^2	0,4	2,45	7 340	2,74	8 230	3,00	9 000	3,23	9 680	3,43	10 300
12	1 Mast tip	c^2	0,4	8,16	6 120	9,15	6 860	10,00	7 500	10,75	8 070	11,44	8 550
13	1 Circular walkway	c^2	0,4	1,66	816	1,83	915	2,00	1 000	2,15	1 075	2,29	1 140
14	1 Skeleton mast	$H \cdot c^2$	1,4	19,60	9 800	29,20	14 590	40,00	20 000	51,60	25 800	70,50	35 250
15	1 Mast jacket	H	1,0	2,40	3 600	3,20	4 800	4,00	6 000	4,80	7 200	5,60	8 400
16	8 Guy cables	$H \cdot c^2$	1,4	3,18	6 360	4,74	9 480	6,50	13 000	8,40	16 800	11,45	22 900
17	1 Step bearing	$H \cdot c^3$	1,4	1,47	1 223	2,19	1 640	3,00	2 250	3,88	2 909	5,29	3 960
18	4 Foundation slabs	$H \cdot c^3$	1,4	1,96	1 470	2,92	2 187	4,00	3 000	5,16	3 880	7,05	5 290
19	1 Ladder	H	1,0	0,60	900	0,80	1 200	1,00	1 500	1,20	1 800	1,40	2 100
20	1 Elevator	H	1.0	1,80	4 500	2,40	6 000	3,00	7 500	3,60	9 000	4,20	10 500
21	4 Foundations with excavation	$H \cdot c^2$	1,4	—	5 190	—	7 740	—	10 600	—	13 700	—	18 630
22*)	1/4 = 920/4 m³ Switching shed	v	0,2	—	5 650	—	5 930	—	6 250	—	6 480	—	6 650
23	1/4 = 750 kW Transformers	$(c^3)^{3/4}$	0,45	1,59	6 360	1,81	7 230	2,00	8 000	2,17	8 700	2,33	9 300
24	1/4 = 40 kW Emergency power unit	$(c^2)^{3/4}$	0,45	0,40	2 383	0,45	2 710	0,50	3 000	0,54	3 260	0,58	3 490
25	10,000 m² acquired land	H^2	2,0	—	1 802	—	3 200	—	5 000	—	7 200	—	9 800
26	1/4 Internal equipment	v	0,2	0,93	2 707	0,96	2 870	1,00	3 000	1,04	3 110	1,07	3 210
27	1/4 Installation	$(v^2)^{3/4}$	0,45	0,20	1 986	0,23	2 260	0,25	2 500	0,27	2 700	0,29	2 900
28	1/4 Measurement instruments	$(c^2)^{3/4}$	0,45	—	1 590	—	1 806	—	2 000	—	2 170	—	2 330
29	2 Centrifugal governors + linkage	$(c^2)^{3/4}$	0,45	0,40	1 590	0,45	1 806	0,50	2 000	0,54	2 170	0,58	2 330
30													
1—30	Total			91,88	193 632	113,94	220 101	136,75	265 550	159,87	300 945	192,22	343 959
31	Freight for 500 km @ 50 DM/t	G	—	90,00	4 500	115,00	5 750	140,00	7 000	160,00	8 000	195,00	9 750
32	Assembly	H^2	2,00	—	10 800		19 400		30 000		43 200		59 000
33	Licenses, Commissions, etc.				208 982 40 000		245 251 50 000		302 550 60 000		352 145 70 000		412 769 82 500
34	Other				248 982 1 018	1,06	295 251 4 749	3,25	363 420 2 150	0,13	422 145 2 855	2,78	495 269 4 731
35	Effective yearly output			90,00	250 000	115,00	300 000	140,00	365 000	160,00	425 000	195,00	500 000
36				1 567 000 kWh		1 860 000 kWh		2 125 000 kWh		2 370 000 kWh		2 600 000 kWh	
37	Yearly overhead 11% Personnel and administration			27 500 17 000		33 000 17 000		40 000 17 000		46 800 17 000		55 000 17 000	
38	Total yearly overhead			44 500		50 000		57 000		63 800		72 000	
39	Generating costs, pfennigs/kWh			$\frac{44\,500}{1\,567\,000} = 2{,}84$		$\frac{50\,000}{1\,860\,000} = 2{,}69$		$\frac{57\,000}{2\,125\,000} = 2{,}69$		$\frac{63\,800}{2\,370\,000} = 2{,}69$		$\frac{72\,000}{2\,600\,000} = 2{,}77$	

*Items 22 through 28 assume that four "ZYKLON-D 30" WPPs are connected to a wind-power center; 1/4 of total cost is therefore given.

TABLE 2. CONVERSION FACTORS.

H_x (m)	$\frac{H_x}{H_0}$	k	$\left(\frac{H_x}{H_0}\right)^k$	H_x (m)	$\frac{H_x}{H_0}$	k	$\left(\frac{H_x}{H_0}\right)^k$
30	0,6	0,2	0,9031	60	1,2	0,2	1,0370
		0,4	0,8156			0,4	1,0755
		0,45	0,7944			0,45	1,0855
		0,6	0,7362			0,6	1,1150
		1,0	0,6000			1,0	1,2000
		1,4	0,4898			1,4	1,2910
		2,0	0,3606			2,0	1,4390
40	0,8	0,2	0,9563	70	1,4	0,2	1,0695
		0,4	0,9145			0,4	1,1440
		0,45	0,9036			0,45	1,1635
		0,6	0,8748			0,6	1,2240
		1,0	0,8000			1,0	1,4000
		1,4	0,7295			1,4	1,7620
		2,0	0,6401			2,0	1,9605

The yearly power outputs in item 35 vary as v^3, i.e. as $(H_X/H_0)^{0.6}$. Generating costs are plotted in Fig. 2 as a function of the height ratio H_X/H_0 and WT operating height H_X. The graph shows that the described "ZYKLON-D 30" WPP is most economical with a WT operating height of about H = 50 m. This economically most favorable operating height of 50 m applies to the 30-m WT. Changes in WT diameter also affect optimal operating height. The studies showed quite clearly, however, that heights of several hundreds of meters, as have been occasionally proposed, would never be justified. Regarding the dimensions of a WPP for the public power supply, a WT diameter of 30 m and an operating height for the WT of 50 m can be considered the technical and economic optimum under normal conditions.

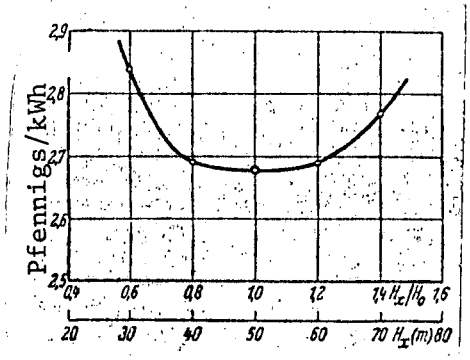

Fig. 2. Generating costs as a function of wind turbine operating height.

3. Dynamic-Pressure Assumptions for Wind-Driven Power Plants

The individual characteristics of structures are in no way taken into consideration in regulations concerning dynamic-pressure assumptions for above-ground structures; such regulations can vary considerably between countries. In the case of a WPP, for example, wind thrust is

concentrated at the height of the WT. In spite of this, dynamic pressure might be assumed to be q = 250 kg/m^2 at a height of 200 m for large-scale WPP projects, in compliance with building regulations, but according to Table 3, it is necessary to reckon with a value of q = 385 kg/m^2. The same applies to the hurricane velocity of 50 m/s to be expected as measured at a height of 25 m, which according to Table 3 increases to 71 m/s at a height of 200 m.

TABLE 3. INCREASE IN DYNAMIC PRESSURE WITH HEIGHT ABOVE THE GROUND.

H (m)	v_x (m/s)	v_{max} (m/s)	q_{max} (kg/m^2)	H (m)	v_x (m/s)	v_{max} (m/s)	q_{max} (kg/m^2)
0	0,00	0,0	0	50	7,10	56,0	240
5	4,55	35,8	98	60	7,30	57,5	253
10	5,40	42,5	139	70	7,45	58,7	264
15	5,85	46,0	162	80	7,60	60,0	275
20	6,15	48,5	180	90	7,75	61,0	285
25	6,35	50,0	192	100	7,90	62,0	295
30	6,55	51,5	203	150	8,50	67,0	344
35	6,70	52,8	214	200	9,00	71,0	385
40	6,85	54,0	223	250	9,40	74,0	420
45	6,38	55,0	232				

It is advisable to base the strength calculations for wind-driven power plants on the dynamic pressure actually to be expected at various heights, since we obtain clarification regarding wind conditions at the construction site for a power plant anyway during planning. If v = 50 (m/s) is the maximum wind speed to be expected at a height of 25 m in Central Europe, and we base our calculations on the probable increase in wind with height (as shown in Fig. 2), we can determine wind pressure for any height using the dynamic-pressure formula $q = \varrho_{0/2} \cdot v_{max}^2$. If we take possible clouds of snow, water and sand (sand storms) into consideration and assume the specific density of air to be γ_0 = 1.50 (kg/m^3) instead of a mean value of 1.22 for pure air, then $q = \gamma_{0/2g} \cdot v_{max}^2 = 0{,}0766 \cdot v_{max}^2$ yields the dynamic-pressure values given in Table 3 and the curve shown in Fig. 3 for dynamic pressure versus height above the ground.

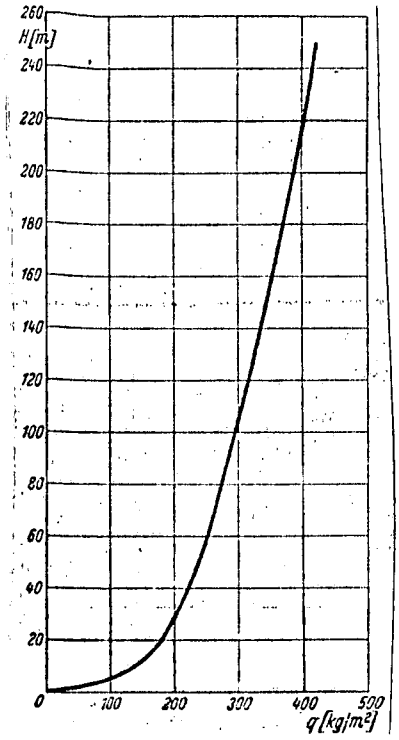

Fig. 3. Increase in dynamic pressure with height above ground.

The wind pressure on a body is then found to be $W = c_W \cdot q \cdot F$ (kg), where F is the largest cross-sectional area perpendicular to the wind direction (principal frame) and c_W is the resistance coefficient for the particular body.

4. Steel-Structure Layout for Wind-Driven Power Plants

WPPs are above-ground structures which experience very high peak thrusts. For a 30-m WT, with v = 16 m/s, taking a gust velocity of 20 m/s into consideration, axial thrust during normal operation is

$$S_{max} = c_w \cdot \gamma_{o_{2g}} \cdot v^2_{max} \cdot F = 0.8 \cdot 0.0766 \cdot 400 \cdot 706.9 = 17\,300 \text{ kg} = 17.3 \text{ t.}$$

In such cases, the guyed mast mounted so as to rotate on a central foundation is found to be economically superior. In order to reduce unsupported length and for the sake of easier installation and greater operating safety, a second guy system is recommended at half its height. The inside of the mast should permit convenient and protected access to the platform and the generator nacelle and, if appropriate, should permit the installation of an elevator. These requirements are best satisfied by a tubular mast in a monocoque design with columns, stringers, and circular ribs. The nacelle, shown in Fig. 4, and the nacelle shaft should likewise be fabricated in a monocoque design. The WT shaft serves as the principal weight-bearing member here, about whose axis the nacelle is built up concentrically of ribs, stringers, and the sheet-metal covering, in a stream-lined configuration.

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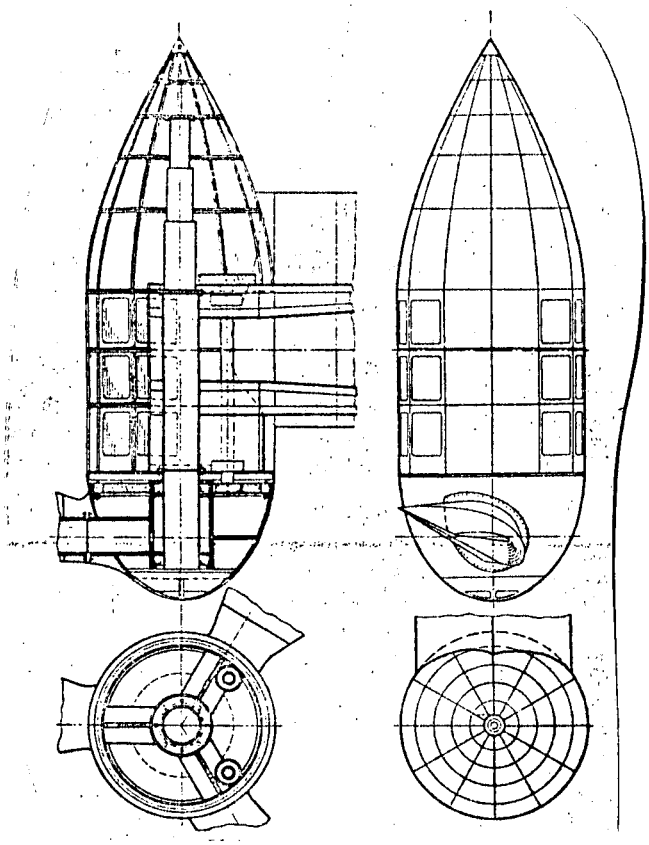
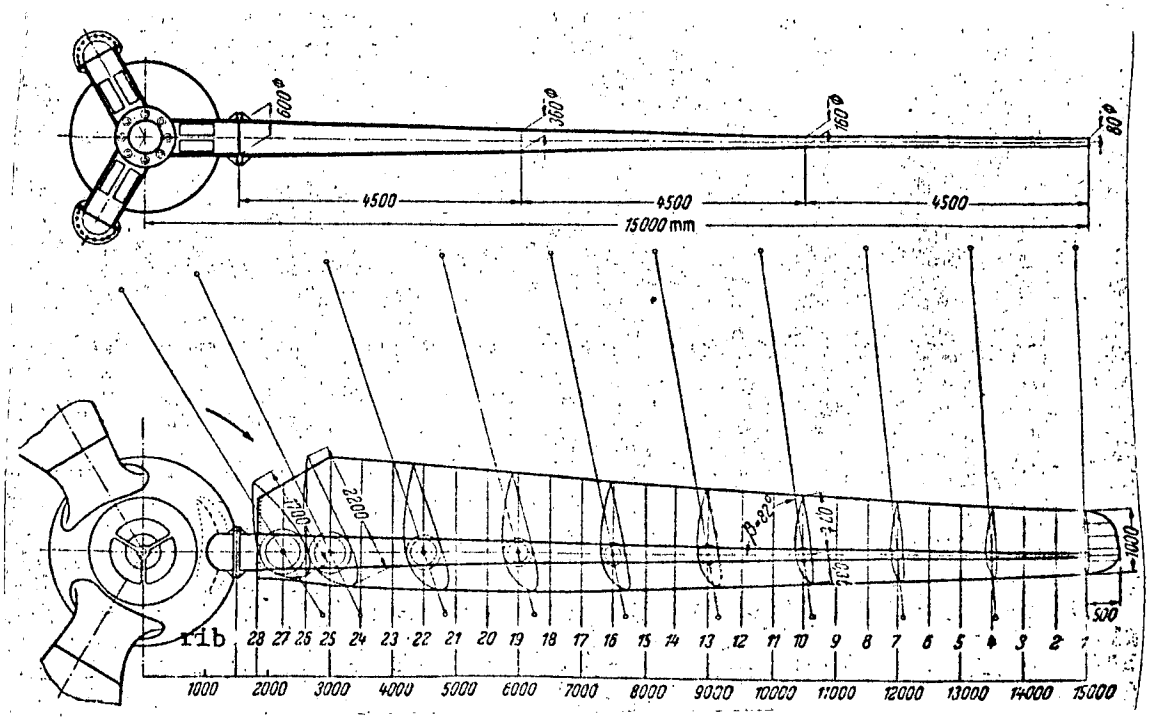


Fig. 4. Nacelle for the wind-driven power plant.

The WT hub consists of a cylindrical bush, a tubular spider and a cap, which are welded together to form a single steel body. The three tubular spokes penetrate the cap and terminate in flanges which are bolted to the blade spars.

More recent WPP designs have WTs with adjustable blades, analogous to the adjustable-pitch propellors on aircraft. The primary intention here is to keep the force of strong gusts from being applied to the blade surfaces in the feathered position. The purpose of this method is not achieved, however, due to the wind structure with its often discontinuous changes in wind velocity and the high inertia of relatively large WT blades. Preference should therefore be given to the sturdier design of a rigid blade system, the so-called ideal WT, which also yields the maximum possible WT efficiency. In any case, it is necessary to take full loading of the blade surfaces in a hurricane into consideration in its dimensioning. The shape and construction of the ideal WT can be seen from Figs. 5 and 6.

The WT assembly is most reliably rotated into the existent wind direction by a "wind rose" system such as found on the Dutch windmill. Turning by means of wind vanes on the basis of the eclipse system, as is conventional in small WPPs, would require dimensions for large WPPs which reduce the profitability and /188 structural stability of the WPP, while adequate directional stability cannot be achieved with a lee arrangement for the WT, as has also been found in practice.



Figs. 5 and 6. Shape and construction of the ideal wind turbine.

5. The Economic Efficiency of Wind-Driven Power Plants

The output of a WT is calculated from the formula

$$N_{WT} = c_l \cdot \varrho \cdot F \cdot v^3 \quad (kW),$$

where ρ = air density $\sim 1/8$ in units of kgs^2/m^4, F is the circular area $D^2\pi/4$, in m^2, described by the points of the WT blades, v is wind velocity in m/s, and c_l is an empirical coefficient. The theoretical maximum of c_l for the loss-free WT is $c_{l\,th} = 0.592$. A value of about $c_l = 0.43$ can be assumed for good WT designs. From this we obtain the N_{WT} values shown in Table 4 for a 30-m WT.

TABLE 4. EFFECTIVE OUTPUT OF A 30-M WT AS A FUNCTION OF WIND VELOCITY.

Wind velocity	v (m/s)	3	5	7	10	13	16	20
WT power	N_{WT} (kW)	5,04	23,3	64,0	186,5	409	726	1430

If we proceed on the basis of wind frequency recorded at the Cuxhaven weather station, on the coastal dike, we obtain the values for yearly effective power generation shown in Table 5 for various "ZYKLON" types of WPPs. According to an officially approved

profitability calculation, the power-production price for the optimal "ZYKLON-D 30" WPP is 2.68 pfennigs/kWh.

TABLE 5. TECHNICAL DATA ON "ZYKLON" WIND-DRIVEN POWER PLANTS.

Type of Wind-Driven Power Plant (WPP)		ZYKLON-D 30	ZYKLON-D 15	ZYKLON-D 7,5	ZYKLON-D 3,75
Diameter of wind turbine (WT)	(m)	30	15	7,5	3,75
Operating height of WT	(m)	50	40	30	20
Maximum height of WPP	(m)	65,00	47,50	33,75	21,875
Diameter of nacelle	(m)	3,00	2,25	1,50	0,90
Diameter of tubular mast	(m)	2,00	1,50	1,00	0,60
Height of circular walkway	(m)	32	30	24	19
Diameter of wind roses	(m)	4	3	2	1
WT speed range	(rpm)	15 ... 60	25 ... 100	45 ... 180	75 ... 300
Wind range used	(m/sec)	4 ... 16	3,5 ... 14	3 ... 12	2,5 ... 10
Nominal wind speed	(m/sec)	9	8,5	8	7,5
Nominal power	(kW)	125	25	5,5	1,2
Peak power	(kW)	700	120	20	2,5
Effective yearly output	(kWh)	2 123 000	450 000	94 000	19 250
Standard voltages	(Volt)				
Direct current		440	440	220	24
Three-phase current		525	525	—	—

6. The Optimal "ZYKLON-D 30" Wind-Driven Power Plant (Fig. 7)

The "ZYKLON-D 30" WPP is equipped with a three-blade WT with a diameter of 30 m. The WT, made completely of metal, is mounted in front of the mast, on the windward side, at the optimum operating height of 50 m. Two wind roses located on the lee side (multibladed WTs) keep the WT assembly, consisting of the WT, the generator nacelle and a streamlined shaft, headed into the wind. The WT assembly can rotate about the tip of the mast in master and neck bearings. The mast is articulated to a concrete foundation and is guyed at heights of 16 and 32 m by steel cables which are anchored to four additional foundations. An elevator leads to a circular walkway located under the WT assembly. From here, the engineer reaches the generator nacelle on a ladder inside the shaft. In the switching shed at the foot of the WPP are housed the transformers (for three-phase operation) or storage batteries (for direct-current operation), a distribution panel, measurement instruments, control instruments, a workshop and housing for the engineer. In dc operation, the WT drives three

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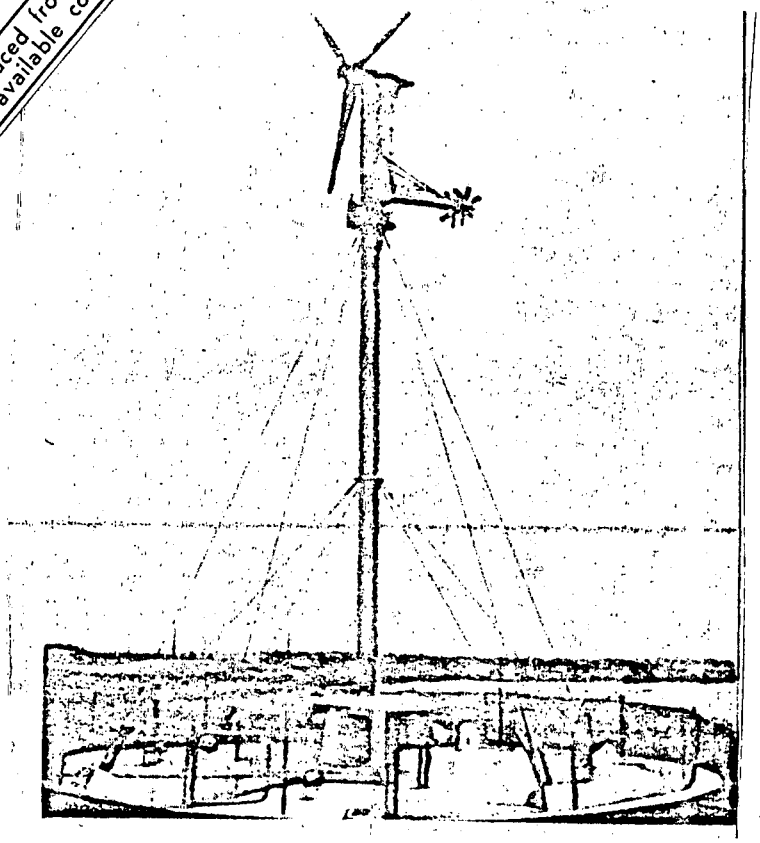

Fig. 7. "ZYKLON" WPP.

dc generators with staggered outputs via a gear train and in three-phase operation drives three three-phase generators via a patented continuously variable gearbox. The rotational speed of the WT, varying between 15 and 60 rpm, is converted into a constant rotational speed by this HVH gearbox. The three-phase output, generated with the same voltage and frequency, can be fed directly into an overland grid system. An automatic regulating provision which is actuated by a control WT at the tip of the gondola and by centrifugal governors ensures the proper gearbox setting and the most favorable rpm and load on the WT. The peak power of the WPP is 700 kW at a wind velocity of 16 m/s (Table 5). The "ZYKLON-D 30" WPP generates 2,125,000 kWh per year, on the basis of the Cuxhaven wind scale (mean wind velocity 8.31 m/s at height of 21 m) and thus supplies light, power and heat for a small city.

REFERENCE

Kleinhenz, "Calculations for and Designing of a Windwheel 130 m in Diameter," Stahlbau 22(3), 49-55 (1953).